The Effect of Global Value Chain Participation on Carbon Embodied in Forest Product Exports: A Quasi-Natural Experiment from the Financial Crisis Shock

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Abstract

Reasonable assessment of the environmental benefits of integrating forest products into global value chains (GVCs) is important to promote sustainable development. Based on the forest product sector data for 41 countries from 2002 to 2014, this paper explores the impact of GVC participation on carbon embodied in exports using the 2008 financial crisis, a quasi-natural experiment of negative global value chain shocks. We found that deepening backward participation in forest product value chains led to more substantial increases in carbon emissions than did forward participation. Countries with large decreases in GVC participation reduced more carbon embodied in forest product exports after the financial crisis (relative to countries with small decreases) through a larger reduction in the scale of forest product exports, and a decrease in the growth rate of capital-intensive products as a result of the relative decline in capital investment. They increased the embodied carbon of exports through a decrease in the growth rate of skilled personnel. Strengthening the technology effect of GVCs with the guidance of skilled forestry personnel is a key way to decrease exported embodied carbon.

A Global Value Chain (GVC) is a transnational production network involving cross-border production chain activities that link production, processing, distribution, and recycling across regions (UNIDO 2002). With the development of GVCs, the threshold for countries to participate in globalization has been significantly lowered, removing the need for countries to establish a complete production capacity from upstream inputs to downstream final products and after-sales services (Xing et al. 2021). However, in academia, the environmental consequences of industry sector participation in GVCs are controversial (Achabou et al. 2017, Liu et al. 2018). Meng et al. (2018) found that carbon emissions along GVCs account for a large proportion of total global CO_2 emissions. Measurements and research related to the "carbon footprint" of the GVC of the forest products sector are also increasing (Lv et al. 2013, Gu et al. 2014, Peng et al. 2022). The unique carbon storage function of the forest products sector plays a crucial role in mitigating climate change, yet it still emits carbon to varying degrees during its participation in global production and processing, which consequently reduces the carbon sink effect (Wang et al. 2014). Domestic products are exported, absorbed and consumed abroad, and the carbon emissions generated in the production process are denoted as export-embodied carbon (Canton 2021). Meanwhile, this paper focuses on wood forest products (hereinafter referred to as "forest products"), including wood, products of wood, cork, paper products, and printing. Measuring the value added and carbon embodied in a country's exports in a particular sector to other countries is necessary because trade policies or environmental barriers are often implemented by importing countries based on specific export sectors (or products; Borin and Mancini 2019).

The Americas and Europe are rich in forest resources and have strong capacity in the processing of forest products.

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These two regions are also important players or even dominant players in the global value chain of forest products. Germany and Italy, together with China, have the widest range of forest product trading partners and are at the core of the value chain network, playing an important "hub" role. In contrast, Central Asian countries have a smaller share and are at the edge of the forest products trade network (Wu et al. 2022). According to Guo et al. (2022), Japan, Australia, South Korea, Israel, and the United Kingdom are the 5 countries with the highest GVC position index of forest products among the 44 countries (Fig. 1). The participation of different countries in global value chains according to their comparative advantages has promoted the redistribution of production factors, but has also led to the transfer of global carbon emissions among different countries and sectors. According to the empirical results of Li et al. (2022), carbon emissions related to GVCs account for 26.2 percent of the world's total carbon emissions in 2015. Shrestha and Sun (2019) revealed carbon emissions from international trade in forest products to account for approximately 25 percent of total emissions from production activities, and the intensity of emissions in developing countries is usually much higher than in developed countries. Clarifying the effects and impact mechanisms of a country's participation in global value chains on the embodied carbon of the forest product sector exports is necessary for policy makers committed to the sustainable development of the forest industry.

This paper examines the effect of GVC participation on embodied carbon in forest product exports. Endogeneity must be considered in this process. For example, a positive correlation between GVC participation and carbon emissions is determined by regression; it is not appropriate to conclude that higher participation of the former will necessarily lead to higher values of the latter. This is because places with high carbon emissions may be the very areas where production plants are concentrated and foreign direct investment (FDI) inflows are higher, leading to a greater participation in the GVC division of the labor system and a two-way causal relationship. In addition, the problem of omitted variables has to be accounted for, particularly for those variables that are related to the explanatory variables yet are unobservable, and once omitted, can cause endogeneity problems. The potential academic contribution of this paper lies in using the impact of the "financial crisis" on forest products GVCs as a quasi-natural experiment to mitigate the endogeneity problem and to assess the direct impact, mechanism, and heterogeneity of GVC participation on the embodied carbon of forest products exports.

Literature Review

This paper builds on the existing literature in the area of embodied carbon and global value chains in forest products trade, including the similar but different areas described in the following:

Literature on the measurement methods and analysis of influencing factors of embodied carbon in the trade of forest products

The Multi-Regional Input–Output (MRIO) model approach is increasingly applied by scholars to measure the carbon associated with forest product trade embodied carbon (Shrestha and Sun 2019, Peng et al. 2022). Unlike the single-region input–output model, the MRIO model assumes that the production technologies of imported and domestic products are distinct, which is more suitable for studying environmental issues related to international trade and can track trade-related emissions. The Antweiler, Copeland, and Taylor modeling framework, referred

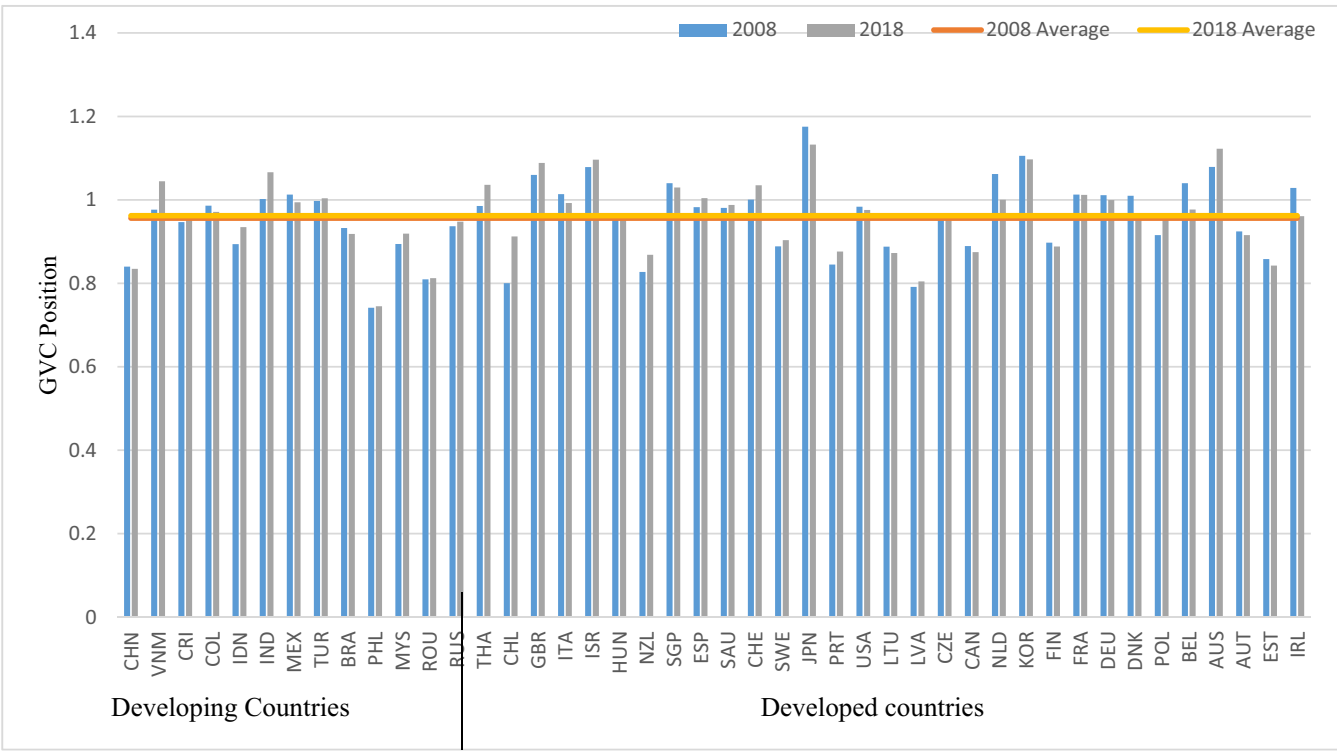

Figure 1.—Distribution of GVC position for forest products between developed and developing countries in 2008 and 2018. (See Appendix A for country abbreviations).

to as "ACT theory," contains scale, structural, and technological effects and is used as the basic theory of trade impacts on climate change (Tamiotti et al. 2009).

Studies on the accounting of indicators of global value chains for forest products and the relationship with trade crises

Academics have proposed a series of indicators to measure the degree of GVC participation (Hummels et al. 2001, Daudin et al. 2011, Wang et al. 2017), and many studies have gradually employed value-added trade decomposition methods to measure forest products GVC participation (Xiong et al. 2019, Hou and Li 2020). However, the specific measures adopted tend to be heterogeneous, and the judgment results are not entirely consistent. In recent studies, scholars have begun to focus on how forest product GVC networks are affected by external shocks such as epidemics (Li et al. 2023, Zhou et al. 2022), providing relevant research on the relationship between trade crises and forest products GVCs.

Research on the impact of GVCs on the trade embodied carbon of forest products and the underlying mechanisms

Studies have examined global environmental issues, such as trade embodied carbon, based on the GVC perspective. A group of studies has shown that participation in GVCs can prevent environmental degradation and save energy (Khattak et al. 2015, Achabou et al. 2017). Participation in GVCs leads firms to reduce pollution emissions from production and exports in participating countries through economies of scale, diversity of intermediate inputs, and quality improvements (Baldwin and Yan 2014), which drive technological progress in participating value chain industries. Other studies suggest that participation in GVCs leads to environmental degradation (Liu et al. 2018). Meng et al. (2015) and Spaiser et al. (2019) argue that most developing countries, such as China, join GVCs and in the early stages of development export large amounts of final products, generating large CO_2 emissions, which makes poorer countries bear the cost of natural consumption. Fei et al. (2020) introduced an aggregate trade accounting approach to construct a GVC impact index and found that the impact of GVC division on embodied carbon emissions increases with deeper GVC participation.

Analysis in the field of forest products

Scholars have calculated the distribution of the carbon footprint in the industry chain within the forest products industry, the industry chain outside the forest products industry, and the trade chain of forest product exports (Lv et al. 2013, Gu et al. 2014). Limited studies have been performed on the relationship between GVC and the trade embodied carbon of forest products (Xie et al. 2021). Hou et al. (2022) attributed the high trade embodied carbon to the low-end embedding of the global value chain due to the participation of the Chinese forest industry in international division.

The existing literature provides important insights for this paper, yet there is still room for progress. First, the endogeneity of GVC participation and embodied carbon in forest product exports are yet to be addressed. Second, there is currently no sufficient evidence to support the theoretical mechanism. This paper examines the relationship between GVC and export-embodied carbon from a counterfactual perspective, using the 2008 financial crisis as a quasi-natural experiment as an instrumental variable for GVC participation. We focus on industry-level impact mechanisms and channels. This paper also investigates how GVC participation affects carbon embodied in exports and confirms that GVC participation brings combined effects of scale, structure, and technology on carbon embodied in forest product exports.

Theory and Methodology

Theoretical analysis

Researchers have demonstrated that international trade has a significant impact on environmental emissions through scale, structure, and technology effects (Grossman and Krueger 1991, Cheng et al. 2018). With the development of GVCs, these three effects are used to elucidate the impact mechanism of GVC participation on carbon emissions (Li and Peng 2011) or carbon efficiency (Sun and Du 2020). The impact mechanisms analyzed in this paper are reflected in the following three aspects:

The first mechanism is the scale effect, denoting the promotion of the scale effect of exported embodied carbon following an increased participation in global value chains. Deeper participation in global value chains in the industrial sector implies the further opening of international trade. This will inevitably lead to the expansion of the scale of economic activities and requires the consumption of large amounts of traditional resources such as fossil fuels, which consequently increases export-embodied carbon (Xie and Zhao 2016). Overall, greenhouse gas emissions generated from the production of forest products are dominated by CO_2 from fuel combustion, which is inextricably linked to the carbon contribution of other industries outside the chain (Gu et al. 2014). Specifically, increased participation in forwarding GVC (the share of intermediate inputs in the composition of exports to other countries) means an increase in domestic value-added exports to downstream links, leading to an expansion of total exports, which will increase the demand for natural resources in industrial production, intensify energy consumption, lead to increased carbon emissions, and pose a threat to the environment. If a country's industrial sector is located downstream of the production and final demand chain, further deepening backward GVC participation (the share of components from other countries in the country's exports of forest products) will drive an increase in total exports and carbon emissions.

The second mechanism is the structural effect, which can be viewed both from the perspective of industrial structure and factor use structure. The former is more applicable to national macro-level analysis, but this paper analyzes the forest products industry from the meso-level, so it focuses on changes in the factor use structure. From the perspective of factor structure, when other conditions are the same, a capital-intensive industrial sector in a capital-rich country will have a dirtier product export mix (Bruneau 2008). The deeper the global value chain, the more investment that will be attracted and the per capita capital increased, which will lead to more production and export of capital-intensive products and an increase in carbon emission.

The third mechanism is the technology effect. It is generally believed that technological effects will inhibit carbon emissions and that a country's industry participation in the global value chain division can affect technological progress through foreign direct investment, technology authorization, and technology spillovers (Glachant et al. 2013).

Higher GVC forward participation means higher demand for technical talent to meet the needs of senior researchers and designers in upstream sectors of product design and development. Higher technology can improve production efficiency and energy efficiency, reduce dependence on energy consumption, and thus limit the increase in carbon embodied in exports.

Quasi-natural experimental selection

In order to determine a suitable instrumental variable to mitigate the endogeneity problem, this paper considers financial crisis as an instrumental variable for GVC shocks. First, the financial crisis is independent of export embodied carbon because it is an external event that cannot be predicted in advance and does not change as a result of the increase or decrease of environmental pollutants. Second, the largest trade contraction since World War II occurred during the financial crisis in 2008. Each national industry and firm that participates in the international division of labor and gains trade benefits through comparative advantage also bears the transmission risk of any economic crisis (Acemoglu et al. 2012). This risk increases incrementally as the value chain lengthens and expands (Giovanni et al. 2018). In 2009, the exports of major intermediate goods from US forest products were severely affected, with particleboard down by 45.58 percent, veneer down by 30.99 percent, and plywood down by 26.17 percent. This accounts for a proportional decline greater than that of China (Wu et al. 2014). In terms of the impact suffered by China's furniture industry, the income of its upstream suppliers of wood raw materials in Southeast Asia also was quickly affected by the ripple effect. Supply chain products with different division of labor positions, such as log products relative to the upstream end and plywood products relative to the downstream end, tend to exhibit significantly different declines following trade shocks (Huang et al. 2012). In this paper, we assess the contagion and propagation of trade shocks in terms of changes in the degree of participation of a country's industry in the global value chain system. Thus, the differences in GVC participation of forest products across countries provide a natural experiment for this paper to adopt the financial crisis as an instrumental variable for GVC shocks.

Measurement model settings

Baseline regression model setting.—In order to test the effect of global value chain participation in forest products on exported embodied carbon, the following was used:

$$lnCO_{2it} = \beta_0 + \beta_1 GVC_{it} + \beta_2 Z_{it}' + \lambda_i + \mu_t + \varepsilon_{it} \quad (1)$$

where i and t represent country and year, respectively; $lnCO_{2it}$ is the logarithm of export embodied carbon; GVC_{it} represents GVC participation; λ_i represents country fixed effects, μ_t represents time fixed effects, and ε_{it} is the error term. Z'_{it} is a series of variables representing time-varying forest industry characteristics and country characteristics. To ensure that the coefficient β_1 on the core variable GVC_{it} is an unbiased estimator, an assumption needs to be satisfied: GVC_{it} and the error term ε_{it} are uncorrelated after controlling for all control variables. To address this identification problem, this paper uses the 2008 financial crisis as an instrumental variable (IV) for GVCs to identify the effect on carbon embodied in forest product exports.

Based on the value chain data of forest product-related sectors in the University of International Business and Economics GVC (UIBE GVC) database in China and the Organization for Economic Co-operation and Development (OECD) database, countries with previously high GVC participation experienced a greater decrease in participation in the wake of the financial crisis shock. Therefore, the sample countries were classified into a treatment group (countries with large changes in GVC participation) and a control group (countries with small changes in GVC participation; Table 1).

The different levels of value chain participation in these countries and the timing of the financial crisis (i.e., 2008) allow us to perform differences-in-differences estimations. More specifically, we compare the change in the embodied carbon of forest product exports in 2008 for countries with large changes in GVC participation (treatment group) with those with small changes in GVC participation (control group) over the same period. The first stage equation for IV estimation described as follows:

$$GVC_{it} = \beta_0 + \eta treatment_i \times crisis_t + \phi Z_{it}' + \lambda_i + \mu_t + \xi_{it} \quad (2)$$

where $treatment_i$ indicates whether country i belongs to the treatment group, 1 if yes, 0 otherwise; $crisis_t$ indicates before and after the financial crisis, 1 from 2009 to 2014 and 0 from 2002 to 2008; ξ_{it} is the error term.

Model settings for mechanism tests.—The growth effect of the trade scale on pollution emissions, factor structure effect, energy saving, and the emission reduction effects of technological progress have previously been reported (Grossman and Krueger 1991, Chen 2009, Gong 2013). This paper focuses on testing whether the core explanatory variable GVC_{pt_f} (the share of intermediate inputs in the composition of exports to other countries) will have an impact on the intermediate variables, and consequently on the level of embodied carbon in forest product exports. The mechanism test model constructed in this paper is as follows:

$$Sca_{it} = \beta_0 + \beta_1 GVC_{it} + \beta_2 Z_{it}' + \lambda_i + \mu_t + \varepsilon_{it} \quad (3)$$

$$Str_{it} = \beta_0 + \beta_1 GVC_{it} + \beta_2 Z_{it}' + \lambda_i + \mu_t + \varepsilon_{it} \quad (4)$$

$$Tech_{it} = \beta_0 + \beta_1 GVC_{it} + \beta_2 Z_{it}' + \lambda_i + \mu_t + \varepsilon_{it} \quad (5)$$

Table 1.—Country grouping.

Treatment group	France, Germany, Bulgaria, Switzerland, Canada, Croatia, Denmark Japan, China, Australia, Brazil, Norway, Greece, Spain Indonesia, UK, Slovakia, USA, Italy, Finland
Control group	Portugal, Sweden, Poland, Latvia, Czech Republic, Slovenia, Austria Netherlands, Malta, Hungary, Belgium, Estonia, Lithuania, Ireland Korea, Russia, Mexico, Cyprus, India, Turkey, Romania

Intermediate variables: the scale effect is measured by the logarithm of total forest product exports (*Sca*); the structural effect is measured by the "capital-to-labor ratio in the forest product sector (*Str*)"; and the "share of higher education (*Tech*)" measures the technology effect, which indirectly reflects the average level of skilled personnel in the industry (Shi et al. 2022). The explanatory variable GVC_{it}, the set of control variables Z'_{it}, and the rest of the model have the same definitions as in the baseline regression model.

Variables and Data

Explained variables

From the bilateral trade of a particular industry, combined with the MRIO model and based on the literature of Peng and Zhang (2016), the embodied carbon in the export of a particular industry from country *i* to country *r* is

$$CO_{2ir} = f_i(I - A_i)^{-1}E_{ir} = f_iB_iE_{ir} \tag{6}$$

where E_{ir} is the column vector of industry-specific exports from country *i* to country *r*, and f_i is the industry-specific carbon intensity vector for country *i* (carbon emissions per unit of output), and both are diagonalized matrices. $B = (I - A)^{-1}$ is the inverse Leontief matrix. Products are divided into intermediate and final goods in the global value chain division system and X_i is the total output column vector for a particular industry in country *i*. Then the composition of the total output is shown in equation (7).

$$X_i = \underbrace{A_{ii}X_i}_{\text{Domestic intermediate goods}} + \underbrace{\sum\nolimits_{r\neq i}A_{ir}X_r}_{\text{Export of intermediate goods}} + \underbrace{Y_{ii}}_{\text{Domestic final product}} + \underbrace{\sum\nolimits_{r\neq i}Y_{ir}}_{\text{Export of final products}} \tag{7}$$

In terms of total sectoral trade, according to equations (6) and (7), the equation for measuring the embodied carbon in the total exports of industry in country *i* can be obtained.

$$CO_{2i} = f_iB_iE_i = f_iB_i\underbrace{\left(\sum\nolimits_{r\neq i}A_{ir}X_r\right)}_{\text{Carbon embodied in intermediate exports}} + f_iB_i\underbrace{\sum\nolimits_{r\neq i}Y_{ir}}_{\text{Carbon embodied in final exports}} \tag{8}$$

Core explanatory variables

The measurement of GVC participation in forest products relies on the forward and backward decomposition of the sectoral value added. Forward decomposition, which corresponds to the decomposition of value added on the production side, reflects how the GDP of each country sector is used to satisfy domestic and foreign final demand. Based on the decomposition model of Wang et al. (2017) and the input–output model, the decomposition of value-added production in the national industry sector contains the following five components:

$$SVA = \underbrace{\widehat{V}L_{ss}Y_{ss}}_{VA_{pdp}} + \underbrace{\widehat{V}L_{ss}\sum_{r\neq s}Y_{sr}}_{VA_{rtp}} + \underbrace{\widehat{V}L_{ss}\sum_{r\neq s}A_{sr}L_{rr}Y_{rr}}_{VA_{sgvc}} + \underbrace{\widehat{V}L_{ss}\sum_{r\neq s}A_{sr}\sum_{u}(B_{ru}Y_{us}) + \widehat{V}L_{ss}\sum_{r\neq s}A_{sr}\left[\sum_{u}\left(B_{ru}\sum_{t\neq s}Y_{ut}\right) - L_{rr}Y_{rr}\right]}_{VA_{cgvc}} \tag{9}$$

where $\widehat{V}$ is the value-added diagonal matrix, $L_{ss} = (I - A_{ss})^{-1}$, A_{ss} is the consumption coefficient matrix within country *s*; A_{sr} is the consumption coefficient matrix from country *r* to country *s*; The total output is denoted as: $X = (I - A)^{-1}Y_{sr} = BY_{sr}$, where *B* is the Leontief inverse matrix and Y_{sr} is the final demand from country *r* to country *s*.

VA_{pdp} represents the domestic value-added production used to satisfy domestic final demand; VA_{rtp} represents the domestic value added in the export of final products, which does not involve a production abroad and is part of traditional or Ricardian trade. VA_{sgvc} is the domestic value added in exports of intermediate goods that are directly absorbed by the importer (simple GVC activity). VA_{cgvc} is the domestic value added embodied in exports of intermediate goods that are used by the importer to produce exports (complex GVC activity) and contains two categories: (1) domestic value added in exports of intermediate goods that are first exported and then repatriated, and (2) those representing the domestic value added in exports of intermediate goods that are absorbed by third countries.

Based on the above decomposition of value added of national industry sectors, the share of the value-added component with intermediate goods crossing borders is defined as the forward participation in global value chains, denoted by GVC_{pt_f}, and measured by

$$GVC_{pt\_f} = GVC_{pt\_f\_s} + GVC_{pt\_f\_c} = \frac{VA_{sgvc}}{SVA} + \frac{VA_{cgvc}}{SVA} \tag{10}$$

Backward decomposition corresponds to the decomposition of value added on the demand side and reflects the sources of final goods and services produced in the country sector. Similar to the above decomposition of value-added production in the country sector, final product production at the country sector level can be decomposed into five components:

$$\underbrace{Y}_{FG} = \underbrace{V_sL_{ss}Y_{ss}}_{DVA_{pdp}} + \underbrace{V_sL_{ss}\sum_{r\neq s}Y_{sr}}_{DVA_{rtp}} + \underbrace{\sum_{r\neq s}V_rL_{rr}A_{rs}L_{ss}Y_{ss}}_{DVA_{cgvc}} + \underbrace{V_s\left(\sum_{r\neq s}B_{sr}A_{rs}L_{ss}\right)Y_s}_{FVA_{sgvc}} + \underbrace{\left[\sum_{r\neq s}V_r\left(\sum_{u\neq s}B_{ru}A_{us}L_{ss}\right)Y_s - \sum_{r\neq s}V_rL_{rr}A_{rs}L_{ss}Y_{ss}\right]}_{FVA_{cgvc}} \tag{11}$$

where, DVA_{pdp} is domestic value added directly, created by producing domestically consumed final products; DVA_{rtp} is

domestic value added directly, created by producing final products for export; DVA_{cgvc} is domestic value added, returned and consumed domestically (complex GVC activities); FVA_{sgvc} is partner value added directly, created in production of domestically consumed products (simple GVC activities); FVA_{cgvc} is foreign value added, created in production of final products, except FVA_{sgvc} (complex GVC activities).

Based on the above decomposition of final product production in the national industry sectors, the share of the value-added component with intermediate goods crossing borders is defined as the backward participation in global value chains, denoted by GVC_{pt_b}, and measured by

$$\begin{aligned} GVC_{pt\_b} &= GVC_{pt\_b\_s} + GVC_{pt\_b\_c} \\ &= \frac{FVA_{sgvc}}{FG} + \frac{DVA_{cgvc} + FVA_{cgvc}}{FG} \end{aligned} \tag{12}$$

Control variables

At the industry level, *ren* is the proportion of renewable energy consumption in the forest products sector to total sectoral energy. Increasing the consumption of fossil energy sources such as coal can significantly increase carbon emissions, whereas substituting the use of renewable energy consumption can effectively reduce carbon emissions. We use *coal* to represent the share of fossil energy of total energy consumption in the forest products sector. The variable *emp* represents the number of people employed in the forest product sector. The more inputs, the more labor-intensive the industry is, and the more the industry can undertake midstream and downstream processes such as production and assembly, which have relatively high carbon emissions (Liddle 2015).

In terms of energy efficiency, *cie* represents carbon emissions per unit of energy consumed and is used to measure the average energy efficiency of a country across sectors, which can affect the green productivity of the forest product sector. Improving energy efficiency is one of the most effective ways to address climate change and reduce sectoral emissions (Yao et al. 2021).

From a macro-aggregation perspective, the annual growth rate of GDP per capita, denoted *pergdp*, is used to measure the level of economic development of a country. Research has determined a significant relationship between environment and growth (Grossman and Krueger 1991). *urbpopr* denotes the growth rate of the urban population. The expansion of urban population represents the growth of urbanization and therefore affects energy consumption and the demand for forest products. One view is that agglomeration has scale and spillover effects that can increase productivity levels, which exacerbate environmental pollution (Zhang and Wang 2014). Other researchers believe that agglomeration reduces pollution emissions through positive externalities and improvements in technology levels (Chen and Hu 2008).

Data sources

The country sample is selected based on the top export value of forest products in terms of value added and data availability. Considering the interference of other trade shock events, such as China's admission to the World Trade Organization (WTO) in 2001 and Sino–US trade friction in 2018, and considering that the industry-level control variables data are from the World Input–Output Database (WIOD; which is only updated to 2014), the sample period is 2002 to 2014 in this study. The 41 countries' embodied carbon data for forest product exports are obtained from the OECD database and calculated by equation (8). The global value chain–related index of forest products is calculated using the OECD Inter-Country Input–Output Tables and UIBEGVC database and equations (10) and (12). The sectoral classification data are taken from the OECD database for D16 (wood and its products) and D17T18 (paper and its products). The data for the three intermediate variables (*Sca*, *Str* and *Tech*) are obtained from the UIBEGVC-OECD database, the WIOD socio-economic accounts, and the World Development Indicators (WDI) database of the World Bank, respectively. The control variables energy efficiency *cie*, *pergdp*, and *urbpopr* are taken from WDI database, and industry-level data energy structure *ren*, *coal*, and the number of employees *emp* are taken from the environmental accounts and socioeconomic accounts of the WIOD. Descriptive statistics of the relevant variables are shown in Table 2.

Results

Analysis of indicator measurement results

A sample of 10 countries that ranked among the top global value added of forest products in 2014 was taken as the sample for the analysis. In the 10 countries from 2002 to 2014 (Fig. 2), there is a significant decline in the forward GVC participation of forest products in Indonesia and Canada, while the other 8 countries were relatively stable. However, in terms of specific years and countries, after the financial crisis in 2008, there were relatively few fluctuations in the forward GVC participation of forest products in China, Japan, Canada, and Germany, while the forward GVC participation of forest products in Indonesia decreased. The forward GVC participation in forest products in Italy increased after the financial crisis. The gap between the forward GVC participation of forest products in these countries converged.

The backward participation of forest product GVCs increased in most countries before 2008 (Fig. 3), except in Canada, Indonesia, and China. There was a consistent turning point in 2008 and, except for Canada, all countries' forest industries were affected by the financial crisis. Developed countries strengthened their control of the downstream forest products value chain by redeveloping forestry manufacturing. As shown in Figure 3, many countries increased their backward participation in forest products after 2009. India continued to decline in 2010 before rebounding; Canada remained relatively stable.

Both forward and backward, the GVC participation of China, the United States, Japan, and India was low, but their value-added output was high (Guo et al. 2022), indicating that their forest product production is not highly dependent on the international division system. Forest products in the European Union countries are generally more dependent on the international market and have a relatively high degree of participation, mainly based on intra-regional trade in Europe.

Canada's carbon embodied in forest product exports continued to decline, with significant fluctuations around

Table 2.—Descriptive statistical analysis of variables. Data sources: Organization for Economic Co-operation and Development database, UIBEGVC database, World Input–Output Database, and World Development Indicators database.

	Variables	Observations	Mean	Standard error	Minimum	Maximum
Explained variable	$lnCO_2$	533	0.127	1.543	−5.521	3.125
Explanatory variables	GVC_{pt_f}	533	0.326	0.155	0.071	0.695
	GVC_{pt_b}	533	0.238	0.078	0.063	0.514
Control variables	*lncie*	533	4.721	1.831	0.842	9.126
	ren(%)	518	0.586	5.913	0.000	0.770
	lnemp	533	5.129	1.704	1.095	10.160
	pergdp(%)	533	2.679	3.77	−14.839	14.231
	urbpopr(%)	533	0.836	1.05	−2.282	4.198
	Coal(%)	518	0.066	0.264	0.000	5.427

the financial crisis in China, the United States, Germany, and Indonesia (Fig. 4). The greatest degree of volatility was in China; exports of embodied carbon emissions increased after its accession to the WTO, to 21.83 million tons in 2007. It fell to 13.7 million tons in 2009 as a result of the impact of the world financial crisis. However, as the world economy recovers, it shows a clear upward trend.

Baseline regression results

The model is estimated using the two-stage least squares (2SLS) method. Table 3 shows the results of the 2SLS first-stage regression. Both GVC forward and backward participation are significantly negatively correlated with the instrumental variables. This indicates that GVC participation significantly declined in the treatment group relative to the control group following the financial crisis shock.

The 2SLS second-stage regressions also indicate that GVC forward and backward participation are significantly positively correlated with the explanatory variables. This shows that the embodied carbon of forest product exports declined more in countries with high GVC participation than in countries with low GVC participation in 2008. Given that countries with high GVC participation in 2008 experienced a greater decline in participation after 2009, these results suggest that the decline in GVC participation reduced embodied carbon in forest product exports.

The simplified panel regression indicates that countries with high changes in GVC participation had relatively less carbon embodied in forest product exports after the financial crisis relative to countries with low changes. This provides further evidence of the relevance of the instrumental variables.

Table 3 also reports the heterogeneity of GVC participation patterns. It reveals that GVC forward participation and GVC backward participation are significantly positively correlated with the explanatory variables at the 1 percent and 10 percent levels, respectively. This indicates that, compared with GVC backward participation, the financial crisis has a more significant impact on GVC forward participation, and the fluctuation of export embodied carbon is more significantly influenced by GVC forward participation.

The forward participation in GVCs was significantly and positively correlated with the carbon embodied in forest products exports. This is not consistent with the findings of Qian et al. (2022), who found that increased forward participation in GVCs at the national level reduced carbon emissions via improved production technologies. This paper looks at the sectoral level and, according to the OECD classification criteria, non–technology-intensive sectors include wood and wood products (D16), paper products, and printing and publishing (D17T18). The deepening of their forwarding participation to achieve emission reductions through technology effects is more limited and may be

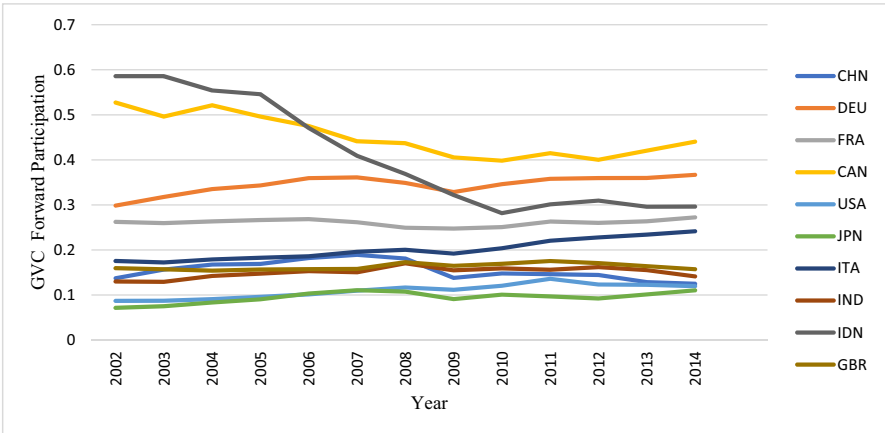

Figure 2.—Trends in GVC forward participation rates for selected National Forest products, 2002 to 2014. (See Appendix A for country abbreviations).

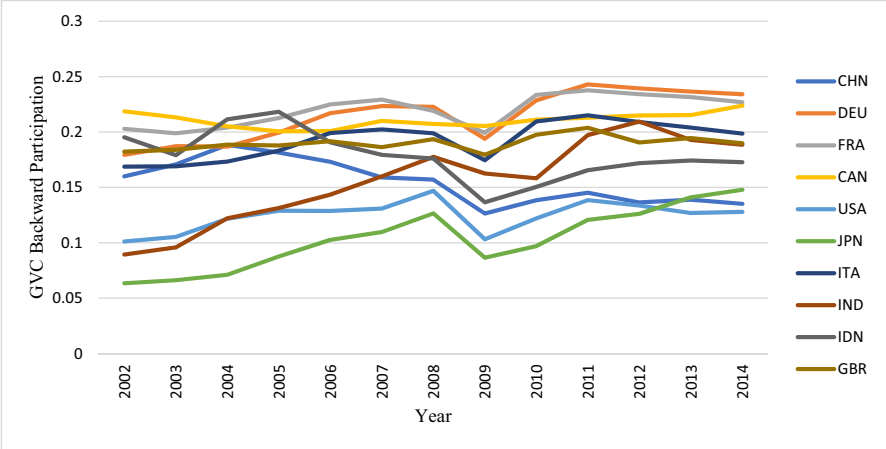

Figure 3.—Trends in GVC backward participation rates for selected National Forest products, 2002 to 2014. (See Appendix A for country abbreviations).

weaker than other effects that play a role in increasing emissions, such as scale.

Backward participation in GVCs is also significantly and positively associated with carbon embodied in forest product exports, as shown in Table 3. These findings show that deepening backward participation in the forest product value chain leads to a more substantial increase in exported embodied carbon than does forward participation. The backward participation is more associated with downstream processing and assembly manufacturing, which is the more energy- and carbon-intensive part of the chain (Zhao et al. 2017). Countries with higher levels of GVC backward participation have low technology content and high embodied carbon emissions from exports (Meng et al. 2018). The increase in backward participation represents an increase in the share of imported foreign intermediate products and a tendency for domestic production chains to move toward the back end. These production chains have backward production technology and high carbon intensity, thus increasing CO_2 emissions (Yu and Luo 2018). The backward participation model enables these countries to participate in GVCs more easily. However, the low level of technology makes the backward participation in value chains have less impact on regional industrial structure optimization and production technology improvement; as such, the carbon embodied in exports increases.

Parallel trend test

Figure 5 presents the change in export-embodied carbon over time for larger (treatment group) and smaller (control group) changes in GVC participation. The coefficients of the interaction terms are not significantly different from zero before the financial crisis shock, which indicates that there was no significant difference between the treatment and control groups before the financial crisis. The export-embodied carbon in the treatment group relative to the control group decreased following the financial crisis, implying that the financial crisis shock had a significant negative effect on the treatment group.

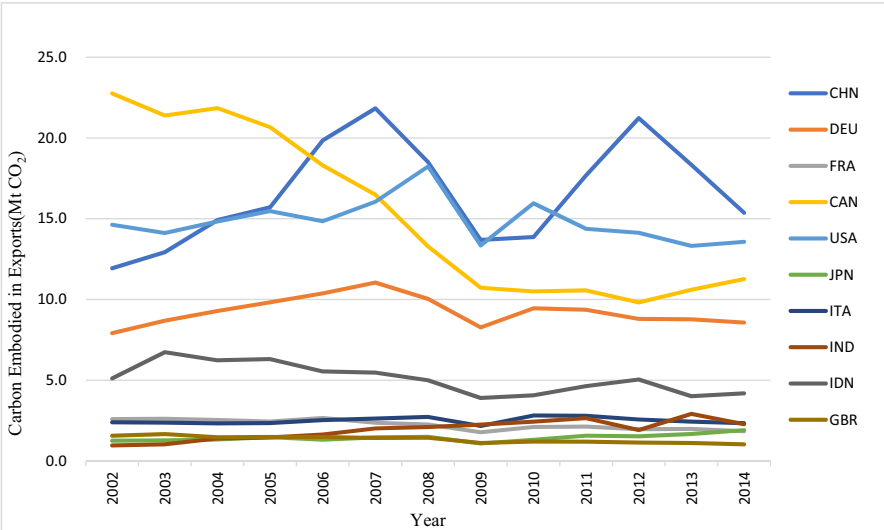

Figure 4.—Trends in carbon embodied in forest product exports in selected countries from 2002 to 2014. (See Appendix A for country abbreviations).

Table 3.—2SLS regression results. Note: (1) Robust standard errors are in parentheses; (2) * P $<$ *0.1,* ** P $<$ *0.05,* *** P $<$ *0.01.*

	GVC_{pt_f} (1)	GVC_{pt_b} (2)	Simplified type (3)
	Panel A. First stage estimation (dependent variable: *GVC*)		
$treatment_i \times crisis_t$	−0.039*** (0.014)	−0.015* (0.007)	
	Panel B. Second stage estimation (dependent variable: $lnCO_2$)		
GVC_{pt_f}	4.802*** (1.543)		
GVC_{pt_b}		12.576* (7.305)	
	Panel C. Simplified estimation (dependent variable: $lnCO_2$)		
$treatment_i \times crisis_t$			−0.185** (0.08)
Observations	518	518	518
Control variables	Yes	Yes	Yes
Year and Country fix effect	Yes	Yes	Yes

Placebo test

To test whether the estimation results are affected by unobservable factors and random factors that cannot be included in the model, 12 countries are randomly selected from 41 countries as the "pseudo-treatment group" and other countries as the control group. Then, "pseudo-shock dummy variables ($treatment_i^{false} \times crisis_t^{false}$)" were generated. The regression results were obtained by repeating the regression 500 times and Figure 6 shows the distribution of the estimated coefficients. The *P* values $>$0.1 indicate that the estimates in this paper could not have been obtained by chance.

Robustness test

We conducted a series of robustness tests by changing the control variables and replacing the explanatory variable "exported embodied carbon" with "production carbon emissions, $lnCO_{2p}$," as shown in Table 4.

By sequentially putting in the two control variables of trade value added of forest products as a proportion of output value, *groexp*, and net foreign investment inflow as a proportion of GDP, *fdi*, the regression coefficients of GVC forward and backward participation are both positive and significant. As shown in the first four columns of Table 4, the results are robust through the empirical results, indicating that an increase in the GVC forward participation and GVC backward participation led to an increase in the embodied carbon of forest products exports.

Columns (5) and (6) of Table 4 reveal that after replacing the explanatory variable with production-based CO_2 emissions, $lnCO_{2p}$, the regression coefficients of GVC forward and backward participation are consistent with that prior to the variable change. Their significance is also observed to be consistent. In summary, both results prove the robustness of the experimental results.

Mechanism test

Table 5 depicts the impact of GVC participation on the size of forest product exports. Column (1) Panel A shows the results of the first stage estimation and shows a significant negative effect on GVC forward and backward participation after the financial crisis. Panel B shows a significant positive effect of GVC forward participation on the scale of

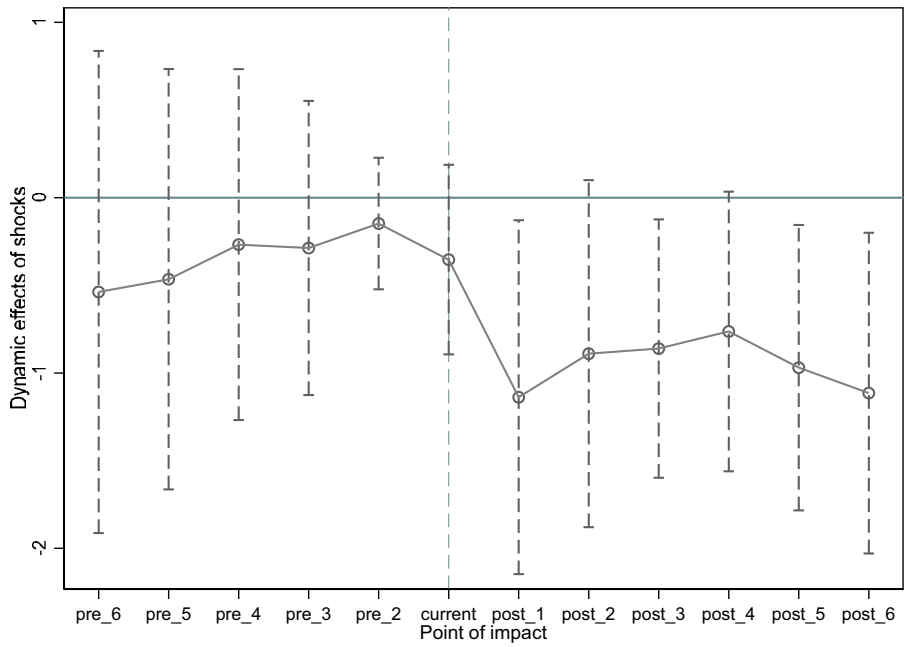

Figure 5.—Parallel trend test. Note: Solid line represents the different temporal trends of export-embodied carbon with larger (treatment group) and smaller (control group) changes in GVC participation. The dashed lines represent the 95 percent confidence interval for the estimated effect.

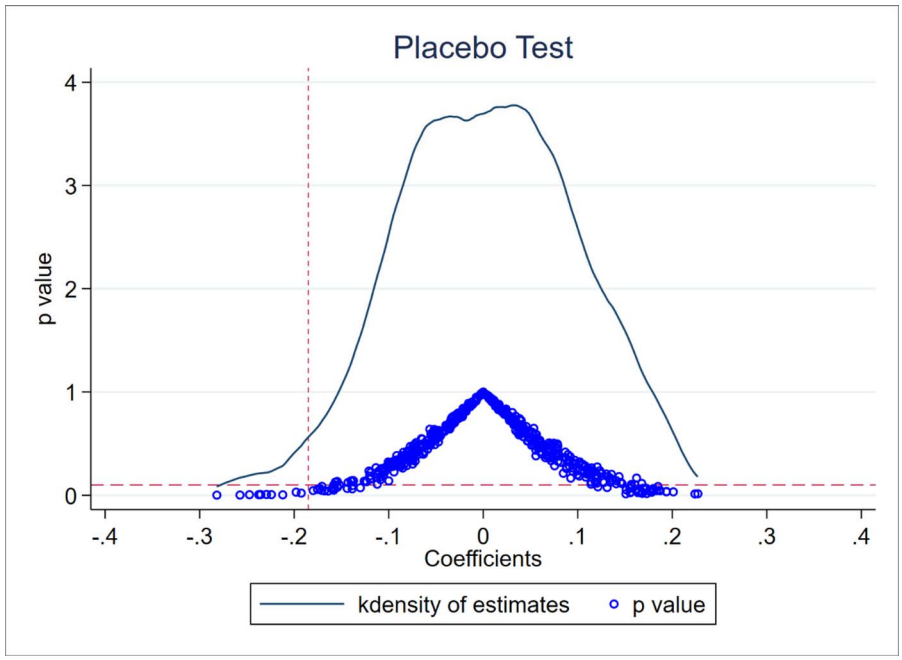

Figure 6.—Placebo test.

forest product exports after fitting the instrumental variables in the second stage. However, the backward effect is not significant. Column (3) further reports the estimation results in simplified form, where the estimated coefficients of the instrumental variables are negative and statistically significant, indicating that countries with large changes in GVC participation reduced the scale of forest product exports relatively more after the financial crisis compared with countries with smaller changes. Exports of embodied carbon decreased. This suggests that a decrease in forwarding participation in global value chains implies a decrease in domestic value added of forest products to downstream links for export, which leads to a contraction in total exports and fewer carbon emissions (Shi et al. 2022).

Did high GVC participation promote capital investment? Column (4) Panel A shows the results of the first stage estimation, where the instrumental variable of this paper is significantly negative for GVC forward and backward participation. Panel B shows the significant positive effect of GVC forward participation on the amount of capital per capita in forest products after fitting the instrumental variables in the second stage, but the backward effect is not significant. This suggests that capital investment is primarily facilitated through GVC forward participation. Column (6) reports the estimation results in simplified form, where the estimated coefficients of the instrumental variables are negative and statistically significant, indicating that countries with large changes in GVC participation have relatively lower capital investment after the financial crisis, which contributes to lower growth rates of capital-intensive products. Carbon embodied in exports decreased.

Column (7) and (8) of Table 5 demonstrates the effect of GVC participation on the proportion of skilled personnel, as measured by the proportion of higher education. The results show that there is a significant positive effect of GVC forward participation on the proportion of skilled talent for the forest products fitted with the second-stage instrumental variables, indicating a lower growth rate of the proportion of skilled talent at low GVC forward participation. However, the backward effect is still not significant. Column (9) of

Table 4.—Robustness tests. Note: (1) Robust standard errors are in parentheses; (2) * P $<$ *0.1,* ** P $<$ *0.05,* *** P $<$ *0.01.*

	Adding *groexp*		Adding *fdi*		Changing explained variable	
	(1)	(2)	(3)	(4)	(5)	(6)
	First stage estimate (dependent variable: *GVC*)					
$treatment_i \times crisis_t$	−0.033** (0.013)	−0.011* (0.006)	−0.033** (0.014)	−0.011* (0.006)	−0.035** (0.013)	−0.013** (0.006)
	Second stage estimate					
	Dependent variable: $lnCO_2$				Dependent variable: $lnCO_{2p}$	
GVC_{pt_f}	5.802*** (1.831)		5.790*** (1.668)		5.364** (2.723)	
GVC_{pt_b}		16.879* (9.457)		16.876* (9.476)		14.101** (5.705)
Observations	518	518	518	518	518	518
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Year and Country fix effect	Yes	Yes	Yes	Yes	Yes	Yes

Table 5.—Influence of forest product GVC participation on its export scale, element structure, and technical talent ratio. Note: (1) Robust standard errors are in parentheses; (2) * $P < 0.1$, ** $P < 0.05$, *** $P < 0.01$.

	GVC_{pt_f} (1)	GVC_{pt_b} (2)	Simplified type (3)	GVC_{pt_f} (4)	GVC_{pt_b} (5)	Simplified type (6)	GVC_{pt_f} (7)	GVC_{pt_b} (8)	Simplified type (9)
Panel A. First stage estimation	Dependent variable: *GVC*			Dependent variable: *GVC*			Dependent variable: *GVC*		
$treatment_i \times crisis_t$	−0.033** (0.013)	−0.011** (0.006)		−0.033** (0.013)	−0.011** (0.006)		-0.036** (0.014)	−0.009 (0.006)	
Panel B. Second stage estimation	Dependent variable: *lnSca*			Dependent variable: *lnStr*			Dependent variable: *lnTech*		
GVC_{pt_f}	5.340*** (1.900)			5.442** (2.764)			3.156** (1.469)		
GVC_{pt_b}		15.535 (10.818)			15.833 (13.479)			13.168 (10.789)	
Panel C. Simplified estimation	Dependent variable: *lnSca*			Dependent variable: *lnStr*			Dependent variable: *lnTech*		
$treatment_i \times crisis_t$			−0.174* (0.090)			−0.177** (0.092)			−0.112** (0.044)
Observations	518	518	518	518	518	518	518	518	518
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year and Country fix effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 5 further reports the estimation results in simplified form, indicating that countries with large changes in GVC participation have a lower growth rate of skilled talent and an increase in the embodied carbon of exports after the financial crisis. This suggests that, if GVC forward participation increases, it will increase the demand for senior researchers and designers in the upstream sectors of production design and development (Shi et al. 2022). High-tech talents can improve the efficiency of resource utilization by mastering advanced science and technology and management experience. This can not only lower the energy consumption per unit of output, but also foster a knowledge and technology intensive growth mode for the industry and provide more exports of clean products. Therefore, the embodied carbon in exports can be reduced to some extent (Guo et al. 2022).

Conclusions and Discussion

The effect of GVC participation on embodied carbon in forest product exports is investigated based on forest product sector data for 41 countries from 2002 to 2014. To alleviate the endogeneity of GVC participation and embodied carbon in exports, a quasi-natural experiment with a negative GVC participation shock (i.e., the 2008 financial crisis) is used as an instrumental variable for GVC participation. The impact of GVC participation on embodied carbon in forest product exports is then evaluated. More specifically, the difference in embodied carbon in forest product exports between countries with more reduced GVC participation after the 2008 financial crisis (treatment group) and countries with less reduced GVC participation (control group) is compared by a double difference method. The reduction in GVC participation was observed to significantly reduce the embodied carbon of forest product exports. Considering the heterogeneity of forest product GVC participation patterns, deepening backward participation in forest product value chains may lead to a more substantial increase in carbon emissions compared with forward participation. The results are found to be robust after a series of robustness tests. Furthermore, the instrumental variables approach is used to examine the influencing mechanism of forward GVC participation on embodied carbon in forest product exports. Compared with countries with small changes in GVC participation, countries with large changes are determined to reduce embodied carbon in exports after the financial crisis through a relatively larger reduction in the scale of forest product exports and a relative decrease in capital investment. This in turn leads to a decrease in the growth rate of capital-intensive products and an increase in embodied carbon in exports through a relative reduction in the proportion of skilled personnel. The relative decrease in the growth rate of skilled personnel subsequently increases the embodied carbon in exports.

This paper finds that GVC participation is positively related to embodied carbon emissions from forest product exports. This is inconsistent with the findings of Qian et al. (2022), who determined that the increase in forward GVC participation at the national level reduced carbon emissions and was achieved through improved production technology. This suggests that the difference between the industry and national levels can result in distinct findings because the industry level is also subject to constraints such as industry characteristics. Moreover, if an industry sector is not technologically advanced, the deepening of participation may promote the

export of implied carbon emissions. Thus, an effective strategy to accelerate carbon emission reductions in the national forest products sector should focus principally on technological improvements. This paper was constrained by certain limitations but also provides directions for future work. For example, we obtained the data of export and import embodied carbon and other related carbon indicators based on the MRIO model and OECD database. Directly measuring the embodied carbon indicators of global value chain participation based on the value-added framework requires further research and is reserved for future work. Furthermore, knowledge and spatial spillovers provide new perspectives to study the impact mechanism of GVC participation on carbon emissions, yet they were not analyzed in detail here because of the differing focus and space requirements of the paper.

The empirical results of this paper on the relationship between GVC participation and carbon embodied in forest product exports have policy implications for a country's forest industry. First, forest industry development policies aimed at increasing the share of GVC participation need to be pursued with caution because deepening GVC participation is likely to increase export embodied carbon. Second, attention should be paid to the carbon-effect of forest product forward value chain participation—it is necessary to improve the ratio of value-added creation of local enterprises to drive technological upgrading and environmental protection standards of the domestic forest industry. Third, the decline of forward GVC participation will increase the embodied carbon emissions of forest product exports through the decrease of the growth rate of the technical talent ratio. Only when the technological effect created by the GVC participation of the forest industry exceeds the scale effect and structural effect, is it possible to make the embodied carbon emissions of exports decrease. In this regard, human resource development is a prerequisite. The upstream forestry industry has a significant positive effect on the timber industry's participation in GVCs. While continuing to follow the green and sustainable path of forestry, afforestation, and forest use, we should expand forests to form a virtuous cycle of industrial development, all of which cannot be achieved without the cultivation of talent. The supply of talent (i.e., the number of labor force members with higher education in forestry-related fields) is necessary to meet the demand for the timber industry in the global value chain.

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Appendix A.—Abbreviations of countries or regions studied in this article.

Code	Country
AUS	Australia
AUT	Austria
BEL	Belgium
BRA	Brazil
CAN	Canada
CHE	Switzerland
CHL	Chile
CHN	China
COL	Colombia
CRI	Costa Rica
CZE	Czech Republic
DEU	Germany
DNK	Denmark
ESP	Spain
EST	Estonia
FIN	Finland
FRA	France
GBR	Britain
HUN	Hungary
IDN	Indonesia
IND	India
IRL	Ireland
ISR	Israel
ITA	Italy
JPN	Japan
KOR	Korea, Rep.
LTU	Lithuania
LVA	Latvia
MEX	Mexico
MYS	Malaysia
NLD	Ireland
NZL	New Zealand
PHL	Philippines
POL	Poland
PRT	Portugal
ROU	Romania
RUS	Russia
SAU	Saudi Arabia
SGP	Singapore
SWE	Sweden
THA	Thailand
TUR	Turkey
USA	America
VNM	Vietnam